

# NEUTRINOS IN PHYSICS, ASTROPHYSICS, AND COSMOLOGY

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## Abstract

A brief review of neutrino anomalies in particle physics and of the role played by neutrinos in cosmology and astrophysics is presented. The main part of the talk is dedicated to the impact of neutrinos and in particular of neutrino oscillations on BBN and to a possible spatial variation of primordial abundances.

## 1 Introduction: why neutrinos are interesting?

At the present time neutrinos are the only elementary particles that indicate *new physics* beyond the Minimal Standard Model (MSM). Otherwise all experimental data are in perfect agreement with MSM. It is well established that all constituents of matter are three families (or flavors) of quarks and leptons. Each family of quarks may have one of three colors, while leptons are white or colorless. Both quarks and leptons participate in electroweak interactions which are realized by the exchange of massless photons ( $\gamma$ ), coupled to electric charge of particles, and heavy  $W^\pm$  and  $Z^0$  bosons. Since neutrinos do not have any electric charge, they interact only with W and Z. That's why their interactions are so weak at low energies ( $E < M_{W,Z}$ ). Quarks, due to their color charges, interact in addition with 8 colored gluons. These interactions are described by quantum chromodynamics (QCD). This theory well describes all observed phenomena in particle physics and only neutrinos disturb the peace. On the other hand, astronomy and cosmology strongly demand new physics beyond MSM.

Neutrinos play a very important role in astrophysics. Stellar evolution and e.g. supernova explosions would be drastically different without neutrinos. Since heavy

elements, necessary for life, are produced in SN explosions, one may say that life itself strongly depends upon existence of neutrinos. Due to their large penetrating ability neutrinos comes out from the deep stellar interior and could give information about processes in stellar cores. Neutrino telescopes will open (in fact have already opened) a new window in astronomy. Observation of solar neutrinos created serious puzzles that most possibly could be resolved by new phenomena in particle physics (neutrino oscillations) or by something unexpected (really drastically) in solar astrophysics.

In cosmology, neutrinos have strong impact on Big Bang Nucleosynthesis (BBN) and thus determine chemistry of the universe. They could even create chemically inhomogeneous, though energetically smooth, universe. Neutrinos may participate in formation of the large scale structure of the universe, making hot, warm and possibly self-interacting dark matter. Detailed mapping of the large scale structure will permit to measure neutrino mass with the accuracy better than 1 eV. Massive or massless, neutrinos have a noticeable impact on the angular spectrum of cosmic microwave background radiation (CMB) and the future missions, MAP and especially Planck, will determine the number of light species in the universe and measure their masses.

## 2 What do we know about neutrinos.

In the standard model neutrinos possess only weak (and of course gravitational) interactions. Anomalous, even stronger than weak, interactions are not excluded but only between neutrinos and/or some other new not yet discovered particles. Neutrinos are coupled to the intermediate bosons according to:  $W^+ \rightarrow \nu_l l^+$  ( $l = e, \mu, \tau$ ) and  $Z^0 \rightarrow \nu_l \bar{\nu}_l$ . Measurement of the decay width of  $Z^0$  permitted to conclude that the total number of different neutrino species is  $N_\nu = 3.07 \pm 0.12$ , while the combined fit to LEP data gives the more accurate result,  $N_\nu = 2.994 \pm 0.01$  (for this and other limits below see Particle Data Group, 1998).

Electric charge of neutrinos are believed to be exactly zero, while magnetic moment should be non-vanishing. Direct measurements give the upper bounds:  $\mu_{\nu_e} < 1.8 \cdot 10^{-10} \mu_B$ ,  $\mu_{\nu_\mu} < 7 \cdot 10^{-10} \mu_B$ ,  $\mu_{\nu_e} < 6 \cdot 10^{-7} \mu_B$ , where  $\mu_B$  is the Bohr magneton. Studies of the stellar cooling rate permit to obtain much stronger limit:  $\mu_\nu < 3 \cdot 10^{-12} \mu_B$  (see e.g. Raffelt, 1996). These results are about 10 orders of magnitude above the standard theoretical expectations, but in some extensions of MSM  $\mu_\nu$  might be large.

Neutrinos may be massless, but there is no theoretical principle that requests the vanishing of  $m_\nu$ , so it is natural to expect that  $m_\nu \neq 0$ . All direct experiments are compatible with  $m_\nu = 0$  but with a quite different level of precision:  $m_{\nu_e} < 3$  eV,  $m_{\nu_\mu} < 160$  keV, and  $m_{\nu_\tau} < 18$  MeV. Indication for  $m_\nu \neq 0$  comes from possible observations of neutrino oscillations (see below). Two different types of mass are possible for neutrinos: the Dirac mass, that distinguishes particles from anti-particles (such a mass have e.g. electrons), and Majorana mass, that mixes neutrinos and antineutrinos. Majorana mass would induce non-conservation of leptonic charge. From the absence of the double beta-decay of heavy nuclei one can conclude that  $m_M < 0.1$  eV.

Leptonic charge is conserved in all observed up to now reactions, however it is not excluded that it may be strongly non-conserved in neutrino oscillations. The hypothesis that neutrinos might oscillate was proposed in 1957 by B. Pontecorvo and its verification now presents a major challenge in experimental particle physics. Oscillation is a generic phenomenon if neutrinos are massive. Indeed, mass eigenstates normally do not coincide with the interaction eigenstates because the mechanism of mass generation does not know anything about gauge interactions with  $W$  and  $Z$ . Thus for example the electronic neutrino, i.e. the one that coupled to electrons through  $W \leftrightarrow \nu_e e$  could be a superposition of two mass eigenstates:

$$|\nu_e\rangle = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle \quad (1)$$

and e.g.  $\nu_\mu$  is the orthogonal combination of  $\nu_{1,2}$ . The mixing may be more complicated and include all three active neutrinos,  $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$ . Moreover new sterile neutrinos,  $\nu_s$ , may be involved. If all existing data on neutrino anomalies are correct (see below) and the anomalies are explained by the oscillations, sterile neutrinos seem to be necessary.

A very interesting effect may take place in neutrino oscillations in inhomogeneous or non-stationary matter, e.g. in stellar interior or in primeval cosmic plasma. Though neutrinos very weakly interact with matter, their refraction index is still different from unity. And if the mass difference is sufficiently small, the matter effects could be significant and in particular a resonance transition between neutrino flavors could be possible (Miheev and Smirnov, 1985; Wolfenstein, 1978). In this case, even for a very small mixing angle in vacuum, the mixing in matter could be of order unity.

### 3 Neutrino anomalies

The following phenomena in neutrino physics do not fit the MSM expectations:

1. **Deficit of solar neutrinos:** the measured flux of solar neutrinos is approximately twice smaller than theoretical predictions. If this deficit is explained by the oscillations then the following values of oscillation parameters are possible: 1)  $\delta m^2 \approx 5 \cdot 10^{-6} \text{ eV}^2$ ,  $\sin^2 2\theta \approx 6 \cdot 10^{-3}$ ; this is the MSW resonance solution; the mixing could be either with an active neutrino or a sterile one; 2)  $\delta m^2 \approx 5 \cdot 10^{-5} \text{ eV}^2$ ,  $\sin^2 2\theta \approx 0.75$ ; 3) “just so” vacuum solution:  $\delta m^2 \approx 8 \cdot 10^{-11} \text{ eV}^2$ ,  $\sin^2 2\theta \approx 0.75$  (for the review see e.g. Bahcall et al, 1998). Long base-line experiments, in particular, CERN neutrinos registered in Gran Sasso, could fix the parameters.

**Deficit of atmospheric  $\nu_\mu$ :** the flux of  $\nu_\mu$  observed in cosmic rays is twice smaller than predicted. The recently measured angular dependence (SuperKamiokande, 1998) gives a strong argument in favor of the mixing of  $\nu_\mu$  with  $\nu_\tau$  or  $\nu_s$  with

$\delta m^2 = 2.2 \cdot 10^{-3} \text{ eV}^2$  and  $\sin 2\theta \approx 1$ .

**Direct observation of neutrino oscillations** (LSND, 1998):  $\nu_\mu$  produced by the decay  $\pi \rightarrow \mu + \nu_\mu$  induce the reactions  $\nu + C \rightarrow e^- + X$ , i.e. electronic neutrinos were generated by muonic ones:  $\nu_\mu \rightarrow \nu_e$ .

**KARMEN anomaly (1995, 1999)**: neutrinos produced by pion decay at rest were registered at a certain distance behind a shield. The moment of the pion production was well fixed. The time distribution of the events should follow the pion decay exponent. However a considerable excess of the events was observed. This excess can be explained by a production of a heavy ( $m = 33.9 \text{ MeV}$ ) sterile neutrino that slowly propagated to the detector and decayed there (Barger et al, 1995). This interpretation however meets serious problems with cosmology and astrophysics (Dolgov et al, 2000a).

## 4 Cosmological limits on neutrino mass

Cosmology permits to put strong limits on neutrino mass. The first limit was derived by Gerstein and Zeldovich in 1966. The number density of relic neutrinos at the present time can be calculated if they were in thermal equilibrium in the early universe:  $n_{\nu_a} = n_{\bar{\nu}_a} = 3n_\gamma/22 = 56/\text{cm}^3$ . This result is true for any stable neutrino with normal weak interactions and the mass below a few MeV. From this expression follows

$$\sum_a m_{\nu_a} = 94 \text{ eV} \Omega_\nu h_{100}^2 \quad (2)$$

where  $h_{100} = H/100 \text{ km/sec/Mpc} \approx 0.65$  and  $\Omega_\nu = \rho_\nu/\rho_c$ . Definitely  $\Omega_\nu < 1$  and thus  $\sum m_\nu < 40 \text{ eV}$ . However, neutrinos cannot dominate the energy density of the universe, otherwise the structure formation at large  $z$  (at early time) would be suppressed. For a flat  $\Lambda + \text{CDM}$  model with  $\Omega_m = 0.3$  the sum of neutrino masses is bounded by  $\sum m_\nu < 2 \text{ eV}$  (Fukugita et al, 2000). The future sensitivity of detailed

galaxy surveys and of CMB angular spectrum is expected to be sensitive to  $m_\nu \leq 1$  eV.

Very heavy neutrinos with mass above 45 GeV are not excluded by LEP measurements and in a large mass interval they are permitted by cosmology. Heavy neutrinos more efficiently annihilate in the early universe. Their annihilation cross-section is proportional to  $m_\nu^2$  for  $m_\nu < m_{W,Z}$ , while at higher energies it is inversely proportional to  $m_\nu^2$ . Correspondingly neutrinos with mass in the interval from 2 GeV up to approximately 100 TeV are allowed by cosmology. There are no reliable calculations of the cosmological mass limits at the heavy end because such a large mass of neutrinos corresponds to the strong coupling regime of the electroweak theory.

If neutrinos constitute *all* dark matter in galaxies then their mass should be larger than 100-200 eV (Tremain and Gunn, 1979). This limit is an impressive manifestation of quantum mechanics at astronomical scales. Since neutrinos are fermions, they obey the Fermi exclusion principle and hence one cannot pack too many neutrinos into a galaxy. Correspondingly their mass should be bounded from below to account for all dark matter.

## 5 Neutrinos and big bang nucleosynthesis

There are three physical effects through which neutrinos can effect the creation of light elements:

**Cooling rate of the universe.** Comparing the cosmological critical energy density,  $\rho_c = 3m_{pl}^2/32\pi t^2$ , with the equilibrium energy density of thermal plasma,  $\rho_T = \pi^2 g_* T^4/30$ , one can find the law of the temperature evolution,  $t \sim g_*^{1/2} T^2$ . Here  $g_*$  is the number of particle degrees of freedom in the plasma. During primordial nucleosynthesis  $g_* = 10.75$ . Each neutrino plus antineutrino species contributes into this number 7/4. A change in the number of particle species would change the

temperature of neutron-proton freezing,  $T_f \sim g_*^{1/6}$ , and also change the moment of the onset of nucleosynthesis. The latter takes place when  $T \approx 65$  keV but the time when such temperature is reached depends upon  $g_*$ . Correspondingly the number of neutrons that survived the decay till beginning of light element formation would be different. Combination of these two effects results in a change of mass fraction of  ${}^4\text{He}$  by 4% if the number of neutrino species is changed by 1. This phenomenon was first noticed by Hoyle and Taylor in 1964 and later by Peebles (1966). Detailed calculations were done by Shvartsman (1969) and Steigman et al., (1977).

According to the recent analysis (Tytler et al 2000) the data permits not more than 0.2 extra neutrino species at BBN. However the conclusions of the earlier paper (Lisi et al, 1999) is that one should be rather cautious in interpretation of the data and a safer limit is  $\Delta N_\nu < 1$ . Moreover there is a conflicting evidence of possible high and low primordial deuterium (see the next section).

**Lepton asymmetry.** The standard calculations of primordial abundances of light elements are done under assumption of vanishingly small lepton asymmetry. However the cosmological asymmetry in lepton sector is unknown and comparison of the BBN calculations with observations permits to put some limits on the value of the asymmetry. If one parameterizes neutrino distribution by the equilibrium function with a non-zero chemical potential,  $f_\nu = [1 + \exp(E/T - \xi)]^{-1}$  the following upper limits on values of  $\xi$  can be established:  $\xi_{\nu_e} < 0.03$  and  $\xi_{\nu_\mu, \nu_\tau} < 3$ . The results are more sensitive to the asymmetry in the sector of electronic neutrinos because the latter directly influence the  $n/p$ -transformation through the reactions  $n + \nu_e \leftrightarrow p + e^-$  and  $n + e^+ \leftrightarrow \bar{\nu}_e + p$ , while  $\nu_\mu$  and  $\nu_\tau$  effect the cooling rate only.

**Neutrino spectrum.** It is assumed normally that  $\nu_e$  participating in  $n \leftrightarrow p$ -reactions have thermal spectrum. However even in the standard model their spectrum differs from the thermal one by roughly 1% (Dolgov and Fukugita, 1992a; Dodelson and Turner, 1992; Hannestad and Madsen, 1995; Dolgov et al, 1997). The impact

of this spectral distortion on the light element abundances is very small, at the level of  $10^{-4}$ , but in some modification of the standard model (in particular if there are oscillations between  $\nu_e$  and  $\nu_s$ ) the effect may be significant.

## 6 Possible spatial variation of primordial abundances

The standard cosmological model satisfies *cosmological principle* stating that the universe is the same everywhere. A strong argument in favor of this hypothesis is that the universe is very smooth energetically as is shown by the almost perfect isotropy of CMB. However it is possible to formulate a model that gives a strong variation of the primordial chemical content of the universe at different space points and very low density variation (Dolgov and Pagel, 1999). This work was stimulated by the observation of primordial deuterium at large red-shifts,  $z = 0.5 - 3$ . Different groups observed three different values of the number density of primordial deuterium. Most observations give “normal” abundance,  $D/H = (3 - 4) \cdot 10^{-5}$  (see Tytler et al, 2000). This value is observed also in our neighborhood. There are a few observations of high deuterium,  $D/H = (10 - 20) \cdot 10^{-5}$  (Webb et al, 1997, and references therein) and there are even recent observation of the region with a low deuterium,  $D/H = (1 - 2) \cdot 10^{-5}$  (Molaro et al, 1999).

If the effect is real its importance for the cosmology is difficult to overestimate. Since the characteristic scale of variation is very large (more than several hundred Mpc), the proper conditions should be arranged during inflationary stage. A model of leptogenesis, that can explain the observed variation (Dolgov and Kirilova, 1991; Dolgov, 1992b), is based on the Affleck and Dine scenario (1985) that gives a large lepton asymmetry together with a small baryon asymmetry. Moreover, the cosmological lepton asymmetry in this model could be non-uniform with a characteristic



scale of variation bigger than several 100 Mpc. To escape large angular fluctuation of CMB temperature one has to assume that there exists “lepton conspiracy” (Dolgov and Pagel, 1999), ensuring a symmetry with respect to permutation of different chemical potentials (electronic, muonic, and tauonic).

The model predicts that there should be three regions on the sky: 2/3 are normal with the standard abundances; 1/6 has low deuterium and the other 1/6 has high deuterium. In the regions with normal deuterium the mass fraction of primordial  ${}^4\text{He}$  is also normal,  $Y_p \approx 25\%$ . In deuterium poor regions  $Y_p \approx 12\%$ , and in deuterium rich regions there is a lot of helium,  $R \approx 50\%$ . Surprisingly, no data at the present time exclude such unusual regions situated at the distances of several hundred Mpc (or larger).

Independently on the model and the data on primordial deuterium, it is an important question: what are the limits on the mass fraction of the second most abundant element in the universe,  ${}^4\text{He}$ , at large distances? A possible indication for a high or low fraction of  ${}^4\text{He}$  could be a different stellar evolution. However stars are not resolved at large distances. One can observe only galaxies and it is difficult to say, if one sees an unusually blue or red galaxy, whether the effect is attributed to an abnormal helium content or to galaxy evolution. Detailed calculations of stellar evolution with high and low initial helium-4 are necessary. For more discussion see the papers by Dolgov and Pagel (1999) and by Dolgov (1999).

Possibly more promising is a search for the variation of helium through the angular spectrum of CMB. The model predicts some peculiar features in CMB angular fluctuations both at high and low angular scales. Especially interesting is the decay of the fluctuations related to diffusion (or Silk) damping (Silk, 1968). The diffusion rate depends upon the number density of electrons prior to hydrogen recombination. In the region with high  ${}^4\text{He}$  the number of electrons is smaller because helium recombined earlier and took some electrons from the plasma. Thus, the damping in such

regions would be stronger. In the regions with low helium the effect is the opposite (Hu et al, 1995). According to the calculations made by P. Naselsky, RATAN-600 is sensitive enough to observe the effect at  $l \sim \text{a few} \cdot 10^3$ . Planck could observe the effect if additional information about the position of poor or rich regions is known. The effect is rather striking: the slope of the angular spectrum of CMB would be very different at different directions on the sky.

## 7 Neutrino oscillations in the early universe and BBN

Neutrino oscillations in the early universe differ from those in stellar interior by two important features: 1) neutrinos may change the medium by back reaction from the oscillations; 2) the loss of coherence is essential and the density matrix formalism should be employed (Dolgov, 1981; Sigl and Raffelt, 1993).

Neutrino refraction index  $n$  in the cosmological plasma was calculated by Nötzold and Raffelt in 1988. There are two types of contribution into  $n$ . The first one comes from the averaging of the neutrino interaction current  $\langle J_\alpha \rangle$ . Due to homogeneity of the universe only the time component of the current gives non-zero contribution proportional to the charge asymmetry of the plasma. The second term comes from non-locality of neutrino interactions due to exchange of intermediate bosons. If charge asymmetry has the normal value  $\sim 10^{-10}$ , the first term is subdominant. However in the case of resonance transition the effect of asymmetry can be strongly amplified. Indeed, the resonance may first take place for neutrinos so that more neutrinos would be transformed into sterile ones by oscillations. This would give rise to an increase of the asymmetry in the active neutrino sector and in turn would enhance the oscillations. In this way an exponential instability with respect to generation of lepton asymmetry is developed. The effect was found by Barbieri and Dolgov in 1991 but

the authors concluded that the back reaction from the plasma quickly turn off the instability. This conclusion was reconsidered by Foot et al (1996) who argued that the back reaction is not so important and that the asymmetry could rise almost to unity. However recent semi-analytical calculations by Dolgov et al (1999c) found a much milder enhancement, by 5 orders of magnitude only. At the moment different groups are in disagreement with each other and the issue remains unresolved. The discussion and the list of relevant papers can be found in Dolgov et al (1999c), Dolgov (2000b), and Di Bari and Foot (2000).

The situation is somewhat simpler in the non-resonance case but still there is a disagreement between the first paper by Barbieri and Dolgov (1990) and all the subsequent ones. While in the first paper it was assumed that the probability of sterile neutrino production is proportional to the inverse annihilation rate of active neutrinos, in the other ones it was argued that the breaking of coherence was determined by the total reaction rate (which is approximately 10 time larger) and this rate must determine the production of  $\nu_s$ . The problem was reconsidered recently by Dolgov (2000) and it was shown that the annihilation rate plays a decisive role in production of  $\nu_s$  in accordance with conjecture of Dolgov and Barbieri (1990).

A resolution of this issues is essential for derivation of BBN bounds on oscillation parameters. According to Dolgov (2000c) the limits are:

$$\delta m^2 \sin^4 2\theta|_{\nu_\mu, \nu_\tau} < 3.3 \cdot 10^{-4} \Delta N_\nu^2, \quad (3)$$

$$\delta m^2 \sin^4 2\theta|_{\nu_e} < 5 \cdot 10^{-4} \Delta N_\nu^2. \quad (4)$$

The last result should be somewhat stronger because electronic neutrinos effect the BBN not only producing a sterile partner but also through their spectrum. Numerical calculations of the last effect were done by Kirilova and Chizhov (1997, 1998a,b) for small  $\delta m^2 \leq 10^{-7} \text{ eV}^2$ . As is argued by Dolgov (2000c) for a larger  $\delta m^2$  the  $\nu_e$  spectrum remains of thermal form but with a non-zero chemical potential. Its impact

on  $n/p$ -ratio permits to exclude mixing of  $\nu_e$  with  $\nu_s$  to the region:

$$\sin^2 2\theta < 0.32 \Delta N_\nu \quad (5)$$

for all  $\delta m^2 > 5 \cdot 10^{-6} \text{ eV}^2$ . BBN limits may essentially reduce the permitted parameter space for the oscillations and more work is necessary to resolve the existing controversies.

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